

# COMPARISON OF AEROSOL CLASSIFICATION RESULTS FROM AIRBORNE HIGH SPECTRAL RESOLUTION LIDAR (HSRL) MEASUREMENTS AND THE CALIPSO VERTICAL FEATURE MASK

S.P. Burton<sup>1</sup>, R. A. Ferrare<sup>(1)</sup>, C. A. Hostetler<sup>(1)</sup>, J. W. Hair<sup>(1)</sup>, R. R. Rogers<sup>(1)</sup>, M. D. Obland<sup>(1)</sup>, C. F. Butler<sup>(2)</sup>, A. L. Cook<sup>(1)</sup>, D. B. Harper<sup>(1)</sup>, K. D. Froyd<sup>(3)</sup>, A. Omar<sup>(1)</sup>

<sup>(1)</sup>NASA Langley Research Center, Hampton, Virginia, USA

<sup>(2)</sup>Science Systems and Applications, Inc., Hampton, VA, USA

<sup>(3)</sup>Chemical Science Division, ESRL, NOAA, Boulder, CO, USA

## ABSTRACT

The NASA Langley Research Center (LaRC) airborne High Spectral Resolution Lidar (HSRL) on the NASA B200 aircraft has acquired large datasets of aerosol extinction (532nm), backscatter (532 and 1064nm), and depolarization (532 and 1064nm) profiles during 18 field missions across North America since 2006. The lidar measurements include scale-invariant aerosol parameters that vary with aerosol type but not concentration. These have been used to qualitatively classify HSRL aerosol measurements into eight separate composition types. The classification methodology uses models formed from “training cases” with known aerosol type. The remaining measurements are then compared with these models using the Mahalanobis distance. Aerosol products from the CALIPSO satellite include aerosol type information as well, which must be inferred using aerosol loading-dependent observations and location information as input to the aerosol retrieval. The HSRL instrument regularly flies over the CALIPSO satellite ground track, presenting the opportunity for comparisons between the HSRL aerosol typing and the CALIPSO Vertical Feature Mask product, giving insight into the performance of the CALIPSO aerosol type algorithm.

## INTRODUCTION

An aerosol classification scheme was introduced in [1] for airborne High Spectral Resolution Lidar (HSRL) measurements from the NASA Langley HSRL instrument. The ability to accurately characterize and discriminate aerosol type can improve both measurement retrievals and modeling, on both a regional and global scale. Since 2006, the NASA Langley HSRL has routinely participated in chemistry and radiation-focused field missions throughout North America, where its high accuracy, high resolution, vertically resolved measurements of aerosol provide vertical context for ground-based, in situ, and satellite observations of aerosols and clouds. The HSRL also routinely provides data for validating the Cloud-

Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar instrument aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite [2]. Furthermore, the HSRL serves as a test-bed for advanced satellite lidar instruments, and the advanced retrievals required for those measurements may benefit from the aerosol classification described here. In this work, we describe the HSRL aerosol classification methodology and do a detailed comparison with the aerosol types that are used in the CALIPSO retrieval [3] for 100 flights of the HSRL along the CALIPSO ground track.

## INSTRUMENT

High Spectral Resolution Lidar instruments have the key advantage over backscatter lidar that it measures aerosol extinction and backscatter coefficients independently, without the need to assume or infer aerosol type. The LaRC airborne HSRL [4] uses the HSRL technique to independently retrieve aerosol and tenuous cloud extinction and backscatter without a priori assumptions on aerosol type or extinction-to-backscatter ratio. Ref. [4] describes the instrument and measurement technique in detail. The HSRL technique is employed at 532 nm and the standard backscatter technique is used at 1064 nm. The instrument also measures depolarization at both wavelengths. Therefore, the HSRL provides vertically resolved measurements of both “extensive” properties that depend on aerosol loading and “intensive” or bulk properties. The latter are the lidar ratio (i.e., the ratio of extinction and backscatter), aerosol depolarization ratio, backscatter color ratio, and spectral depolarization ratio (i.e., the ratio of aerosol depolarization at the two wavelengths). The intensive parameters provide information about the aerosol physical properties which are combined to infer aerosol type.

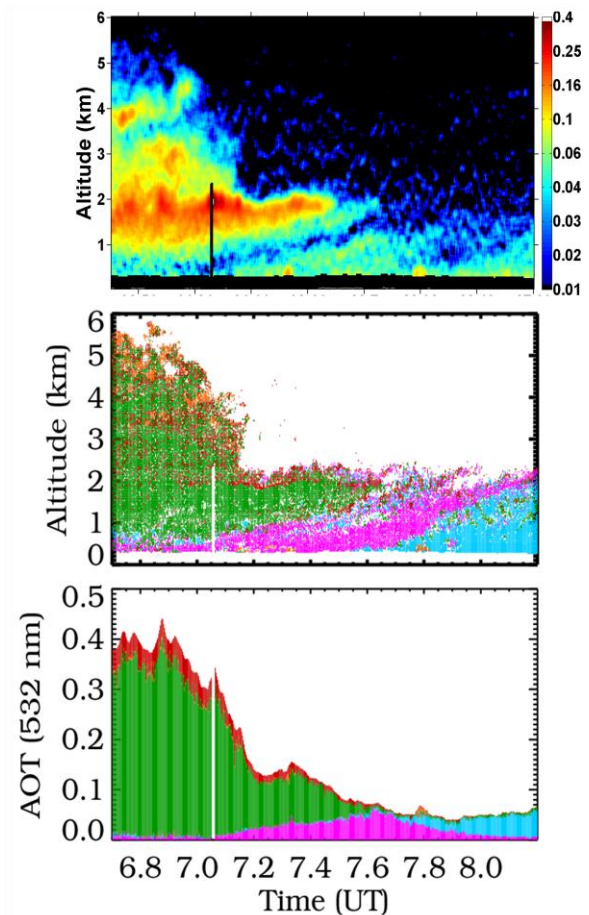
## CLASSIFICATION METHODOLOGY

The HSRL aerosol classification methodology is presented in [1]. The HSRL aerosol classification is performed in two parts. First, specific samples of

known aerosol types are combined to make model multi-normal distributions defined by the 4-by-4 variance-covariance matrix of the four aerosol intensive variables. In the second part of the calculation, the full set of HSRL measurements is classified. The Mahalanobis distance is calculated from each measurement to each class distribution; the minimum distance indicates aerosol type. The Mahalanobis distance is appropriate for quantifying the distance between a point and a distribution, and is therefore a better metric for this application than the Euclidean distance between two points. It assumes the aerosol classes are represented as multi-normal distributions.

The HSRL aerosol classification has eight types and begins with thirty samples of labeled data, between two and six samples for each type, in total about 0.3% of the full dataset. The strategy of using labeled samples to create “seed” aerosol class models to classify all other measurements allows us to incorporate knowledge based on a relatively limited set of observations where the aerosol type is known or easy to infer. Specifically, we incorporate samples of ice haze observed during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) campaign, identifiable by the signature of fall-streaks in the lidar measurements, and pure dust samples from plumes of Saharan dust tracked across the Atlantic by CALIPSO [5] and from a dust storm on the slope of Pico de Orizaba observed during the MILAGRO (Megacity Initiative: Local and Global Research Observations) field campaign [6]. Samples that are labeled dusty mix include cases of locally generated dust with intermediate values of depolarization. Clean air samples in the Caribbean provided most of the labeled samples for the maritime class. Labeling of samples of polluted marine air from the marine boundary layer in the Gulf of Mexico and near the coast of Virginia was justified by back trajectory analysis which tracked the air samples from the marine boundary layer backward to urban areas approximately a day or less earlier. Urban samples are taken where the attribution of elevated levels of aerosol optical thickness (AOT) to urban sources is fairly straightforward. In the case of smoke and fresh smoke, the plume was observed visually from the B200 or was measured by coincident airborne in situ measurements [7] and/or MODIS [8].

The HSRL aerosol extinction and aerosol classification result are illustrated in Fig. 1 for HSRL measurements acquired during a CALIPSO validation flight between Hampton, Virginia and Tampa, Florida on August 8, 2006. Multiple types are layered throughout the depth



*Figure 1. HSRL observations on a flight from Hampton, VA to Tampa, FL on 8 August 2006. Top panel shows aerosol extinction coefficient at 532 nm, middle panel shows aerosol classification mask, where blue represents marine aerosol, pink represents “dusty mix”, green represents urban and red and orange indicate the smoke and fresh smoke categories. The bottom panel shows the apportionment of AOT to the various types.*

of the atmosphere along the track. Aerosol along the northern (earlier) part of the track is dominated by urban aerosol, whereas marine aerosol is evident at the southern (later) end of the track. In between is a layer of Saharan Dust which was advected across the Atlantic. The bottom panel in Fig. 1 illustrates the apportionment of AOT to the various aerosol types.

## COMPARISONS

During the CalNex mission in 2010, a Particle Analysis by Laser Mass Spectroscopy (PALMS) instrument [9] was operated at a ground site in Pasadena. An example showing HSRL aerosol classification along the flight

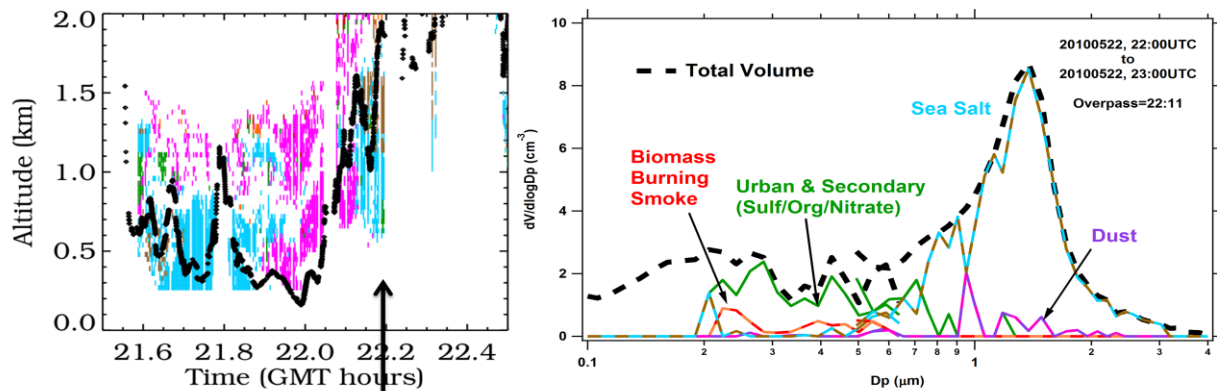


Figure 2. Left panel shows aerosol classification from HSRL. The black trace indicates the height of the mixed layer. The arrow indicates the closest approach to the ground site in Pasadena. The right panel shows size-resolved single particle composition from PALMS. Both datasets indicate dominance by sea salt at the time of the overflight.

track is shown in the left panel of Fig 2. The calculated mixed layer height (based on gradients in aerosol backscattering) is indicated by the black trace and the time of closest approach to the ground site is indicated with an arrow. At the overflight time, the aerosol in the mixed layer is inferred to be maritime and polluted maritime aerosol. This agrees well with the PALMS measurements which are dominated by sea salt.

Validation underflights of the CALIPSO track present the opportunity to compare with the CALIPSO Vertical Feature Mask [3]. In contrast to HSRL, the CALIPSO lidar does not independently measure backscatter and extinction coefficients, and some knowledge of the aerosol type is required input for the retrieval. Aerosol types of individual aerosol layers are inferred from thresholds on attenuated backscatter and depolarization and from layer height and location. Fig. 3 illustrates the

aerosol types determined using HSRL measurements for aerosol layers detected by CALIPSO. All aerosol layers found in 100 flights of HSRL under the CALIPSO track are represented, weighted by layer optical depth. The color coding represents the dominant HSRL-inferred aerosol type for each layer, grouped along the x-axis according to the type assigned by CALIPSO. For the most part there is reasonable agreement. Layers that are assigned *marine* by CALIPSO are inferred to be mostly *marine* or *polluted marine* by HSRL. Likewise, CALIPSO's *dust* is mostly HSRL's *pure dust* or *dusty mix* and CALIPSO's *polluted continental* is mostly HSRL's *urban*. However, almost all of the aerosol in layers that CALIPSO labels as *smoke* is inferred by HSRL to be *urban* aerosol as well. Yet these CALIPSO types result in the same lidar ratio selection so mistyping in these two categories is not of great concern. Indeed, these types are relatively difficult to separate using HSRL measurements as well, partly because of the similarity in lidar ratio. Finally, layers identified as *polluted dust* by CALIPSO correlate with various different aerosol types inferred by HSRL, and this deserves further investigation. Assignment to the *polluted dust* category assumes that these aerosols are made up of a mixture of dust and pollution, so the apparent presence of significant amounts of marine aerosol indicates at least that the mixture is not be well characterized by CALIPSO in some cases. The presence of significant amounts of HSRL's *urban* type in the category *polluted dust* may be less of a concern, but may reflect a misidentification of some layers that would be more appropriately handled as *polluted continental*. Specific case comparisons will be discussed.

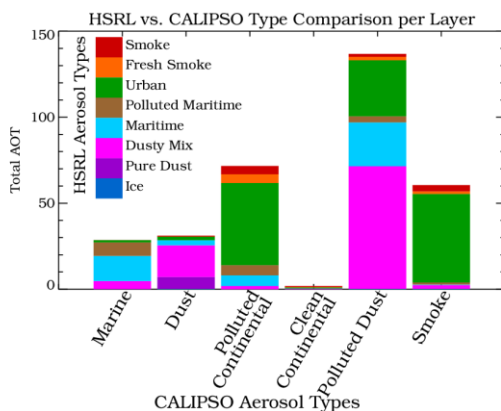


Figure 3. Comparison of aerosol types used by the CALIPSO processing algorithm with the dominant HSRL-inferred type within a layer, weighted by layer

## DISCUSSION

A qualitative classification of aerosol type provided along with quantitative profile measurements of aerosol backscatter and extinction has many useful applications. The products can be used to apportion AOT by type and vertical location in the column, even for scenes with layers of multiple types, which is not possible with passive imaging radiometer and polarimeter measurements. This kind of information is useful for estimating radiative forcing throughout the column and understanding aerosol lifetime and transport. It is also useful for assessing the predictions of transport models, i.e., determining whether the models predict the correct aerosol type at the correct altitude. Data from a future satellite lidar that enables similar skill in identifying type and quantifying aerosol extinction and backscatter would be extremely valuable for assimilation into models [10]. CALIPSO has already provided the first long-term global data set of aerosol vertical distribution; however, errors in the selected lidar ratios due to limited information about aerosol type can affect retrieval accuracy. Based on our results, a future satellite lidar similar to CALIPSO, but with the addition of polarization sensitivity at 1064 nm and the HSRL technique at 532 nm could provide a significant advance in characterizing the vertical distribution of aerosol for climate and air quality applications.

## ACKNOWLEDGEMENTS

Funding for this research came from the NASA HQ Science Mission Directorate Radiation Sciences Program; the NASA CALIPSO project; and the U.S. Department of Energy's Atmospheric Science Program Atmospheric System Research, an Office of Science, Office of Biological and Environmental Research program, under Grant No. DE-AI02-05ER63985. The authors also acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and READY website (<http://www.arl.noaa.gov/ready.php>) used for some of the analysis described in this presentation. The authors would also like to thank the NASA Langley B200 King Air flight crew for their outstanding work in support of HSRL measurements.

## REFERENCES

1. Burton, S.P., et al., *Aerosol Classification of Airborne High Spectral Resolution Lidar Measurements – Methodology and Examples*. Atmospheric Measurement Techniques, 2012. **5**(1): p. 73-98.
2. Winker, D.M., et al., *Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms*. Journal of Atmospheric and Oceanic Technology, 2009. **26**(11): p. 2310-2323.
3. Omar, A.H., et al. (2009) *The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm*. Journal of Atmospheric and Oceanic Technology **26**, 1994-2014 DOI: 10.1175/2009jtech.1231.1.
4. Hair, J.W., et al. (2008) *Airborne High Spectral Resolution Lidar for profiling aerosol optical properties*. Applied Optics **47**, 6734-6752 DOI: 10.1364/AO.47.006734.
5. Liu, Z.Y., et al. (2008) *CALIPSO lidar observations of the optical properties of Saharan dust: A case study of long-range transport*. Journal of Geophysical Research-Atmospheres **113**, D07207 DOI: 10.1029/2007jd008878.
6. de Foy, B., et al., *Aerosol plume transport and transformation in high spectral resolution lidar measurements and WRF-Flexpart simulations during the MILAGRO Field Campaign*. Atmospheric Chemistry and Physics, 2011. **11**(7): p. 3543-3563.
7. Warneke, C., et al. (2010) *An important contribution to springtime Arctic aerosol from biomass burning in Russia*. Geophysical Research Letters **37**, L01801 DOI: 10.1029/2009gl041816.
8. Saha, A., et al. (2010) *Pan-Arctic sunphotometry during the ARCTAS-A campaign of April 2008*. Geophysical Research Letters **37**, L05803 DOI: 10.1029/2009gl041375.
9. Froyd, K.D., et al., *Aerosol composition of the tropical upper troposphere*. Atmos. Chem. Phys., 2009. **9**(13): p. 4363-4385.
10. Zhang, J., et al., *Evaluating the impact of assimilating CALIOP-derived aerosol extinction profiles on a global mass transport model*. Geophys. Res. Lett., 2011. **38**(14): p. L14801.